LI. The Hering Color-Blindness Apparatus and the Normal Rayleigh Equation

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In a previous article on the Hering Color-Blindness Apparatus reference was made to experiments then in progress on the normal Rayleigh equation, the matching of spectral red and green to yellow.[1] In this paper we report the results of those experiments. It was our purpose not only to test further the capabilities of the Hering instrument, but also to determine the range and form of distribution of the matches of a large number of *O*'s who have normal color vision. That there is a wide variation among normal *O*'s has, of course, been known since Rayleigh first performed his experiment,[2] but interest has centered upon the extremes of variation (the anomalous trichromats), and the central variations have for the most part been either ignored or else explained away as the result of 'errors of observation.'

Conditions and Procedure of the Experiment. The experiment was performed in a dark room, and the apparatus was illuminated by an artificial light of Gage's glass[3] as described by Cowdrick and Winfield.[4] The horizontal distance from the center of the roundel to the light chamber was 13 cm.; the vertical distance from the top of the table upon which the apparatus stood to the center of the roundel was 27 cm. It was found by test that a variation of from 2 to 12 volts of current below the 110 at our disposal did not affect the results of the experiment. *O*'s eyes were protected from the glare of the lamp by a screen.

In making the equation we place a green glass in the left (to one facing the open side of the instrument), a red glass in the floor, and a yellow glass in the right aperture of the light chamber. The red reflector is set at 20° and the yellow at 15° of arc;[5] the former is

[1] M. Cowdrick and M. Winfield, The Adjustment of the Hering Color-blindness Apparatus, this Journal, xxx, 1919, 418.

[2] Rayleigh, Experiments on Colour, *Nature,* xxv, 1882, 64; On Defective Colour Vision, *Brit. Assoc. Rep.,* 1890, 728. For a review of subsequent experimentation see J. von Kries, in Nagel's *Handbuch d. Physiologie des Menschen,* 1905, 124ff., and in Helmholtz' *Physiologische Optik,* ii, 1911, 343ff.; J. H. Parsons, *Colour Vision,* 1915, 182ff.

[3] We have recently learned that not all roundels of Gage's glass have, as have those employed in this and former experiments in the Cornell laboratory, a ground surface. At the present time the manufacturers supply the glass as it comes from the press unless a ground surface is specified.

[4] *Op. cit.* They give incorrectly the horizontal distance from roundel to light chamber as 'about 30' cm.

[5] This setting of the red reflector was chosen because it permitted a green of excellent chroma at the one extreme of the variable. The 'mixing value' of R in this apparatus is much greater than that of G; *e.g.,* if the red reflector had been set at 40° of arc all the green

not moved throughout the experiment, and the latter is moved only when, after the match in hue has been made, *O* reports a difference in tint. The green reflector which conditions the variable stimulus is set to give R or G as *E* desires. *O* is then instructed to make the equation by turning the knob at his right hand (which controls the green reflector) to the right or to the left, as the case may be, until the match is made. In these experiments ten successive matches were required of every *O*, and the setting of the green reflector for every match was made according to the schema Rl, Gs, Rm, Gl, Gs, Rm, Gm, Rl, Gl, Rs, the capital letters signifying a setting of the reflector that would give R or G, and the small letters long short and medium distances from the approximate degree of arc that would give the match. In order to avoid the effect of local adaptation (which is an important source of variation in a single set of matches) *O* after making a match was required to rest his eyes for a few moments and then to verify, and if necessary to rectify, the equation before the scale-reading was recorded.[6] In all matches *O* used but one, usually the right, eye.

Results. Our results fall, according to the aim of our investigation, into two groups: those which concern the capabilities of the Hering Color-blindness Apparatus, and those which indicate the range and distribution of the matches of normal *O*'s. As regards the first of these, we found early in our experimentation that the apparatus, when employed under the conditions we have described, gives homogeneous results; but that, owing to the mechanical adjustment which controls the movements of the reflector, the units of measurement are too large. The adjustment is so 'coarse' that a change in the position of the reflector by less than a degree of arc, an amount that frequently destroys a match, is not easily made. The effect of this is, of course, to reduce the range of positions that for a single *O* will give a match; for example, 1% of our *O*'s gave the same reading 10 times, 2% 9 times, 19% 6 times, and 32% 5 times of a total of ten trials. This quantitative result is, however, conditioned in part upon the fact that *E* read the scale to the nearest degree, a procedure that, in view of other faults in the apparatus, seemed advisable. The size of the arc that carries the scale is so small that *E* could not read to less than ½°, and the distance of the pointer above the scale is so great that unless *E*'s eye is directly above the pointer the error of reading the scale is at least 1°. In the course of our experiments we reduced the error of observation to less than ½° by a five-fold extension and enlargement of both scale and pointer; but for the sake of uniformity we continued, as we had begun, to read to the nearest degree. In all other respects the instrument was entirely satisfactory for our purpose; it is easily managed, instantly ready for use, and if its position relative to the source of illumination is permanently fixed is always reliable.

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at our disposal would not have cancelled the red. Our experience has shown that a setting of the red reflector at 25° of arc would have given an R that could have been cancelled by all of our *O*'s, and the resultant yellow would have been of lighter tint and better chroma than that which we obtained in this experiment.

[6] In an extended series of observations with a single *O* who adapts slowly in the dark we found that general adaptation upon coming from a light into the dark room did not, after the first three or four minutes, make any sensible variation in the average equations.

As regards the distribution of the matches of normal *O*'s, we give the results of 100 cases. Many more than these were collected; but we have excluded not only those of the preliminary period before we had the apparatus and method of observation under control, but also 10 cases we found to be abnormal in the sense that they were either color-blind or color-weak. When once the final method, which we have described above, was determined upon, we began the collection of the 100 cases, accepting every *O* as he came, and continuing until the hundreth match was obtained. The *O*'s consisted of 36 men and 64 women taken as we found them from the graduate and undergraduate students and from the staff of the department of psychology in Cornell University. We believe that they as a group constitute a fair sample of a university population, and that every individual in the group has normal color-vision. The majority, however, were not tested specifically for color-blindness or color-weakness because indications of abnormality appear in the ordinary course of matching R and G to Y; abnormal *O*'s almost invariably give larger *mv*'s than normal, and they also give an average match that falls at the limits of (or outside) the normal distribution. We, therefore, tested for color-blindness or color-weakness only those individuals whose matches differed markedly from the average, whose *mv*'s were exceptional, and whose color-names in making the match were incorrect; the remainder we assumed to be normal. We give in the following table the distribution of the matches of these normal *O*'s.

TABLE I

DISTRIBUTION OF THE AVERAGE AMOUNTS OF G REQUIRED BY 100 OBSERV ERS TO EQUATE R TO Y

Degrees of Arc.........	45	46	47	48	49	50	51	52
No. of cases...........	1	7	18	23	27	17	6	1

Average = 48.48 Median = 49

The difference between groups represented in the table by apposed degrees of arc is, we believe, highly significant. In the first place, the units of measurement were, as we have seen, too large to admit of minute gradations. Furthermore, the *mv*'s from the averages of every ten matches were small; the average of all these was 0.7°, and their median value was 0.6°; 27% of the *O*'s had an *mv* of 0.5° or less, and only 15% of 1° or more. Finally, if only the conditions were kept constant, we found no greater variation in average matches of a single *O* from day to day. We believe also that, in so far as our experiments go, we have determined the limits of normality; we found no case, normal or abnormal, beyond the limit of 45° (*i.e.*, in the direction of less green); and although nine cases fell beyond 52°, they were all abnormal; only one abnormal, a protanope whose average match was 52°, came within the limits of the normal distribution. If, then, the difference between groups is a real difference, and if we have been successful in finding the limits of normality, the range of distribution becomes significant. The mode is at 49° and the limits are 45° and 52°; there is, therefore a greater

range of distribution on the side of less green than on that of more green. In this respect the form of the curve is like one of 59 cases published by Donders, and consequently it may be that this form is typical.[7] But our own curve permits of another interpretation. It will be observed that, with the exception of the extreme groups, the difference in size of groups becomes progressively less as the mode is approached. Furthermore, the average of all matches is 48.48°, and this average falls between the two largest groups which combined equal half the cases. We might regard the curve, therefore, as broad and flat at the mode, and as falling away equally on the two sides. If, as von Kries suggests,[8] this variation among normal *O*'s has a physical cause, *i.e.*, is due to differences in macular pigmentation, there would seem to be no reason why the curve should not approximate to a normal distribution.

We do not wish, however, to overemphasize the form of distribution. The essential feature of our results is that the extent of variation among normal *O*'s has been brought into bold relief. The fact has, of course, long been known to everyone who has observed students, in demonstration of the first law of color mixture, match R and G to grey; but so far as our reading has gone von Kries is alone in realizing that the variation is distinctive enough to mark off the normal from the anomalous groups.

[7] F. C. Donders, Farbengleichungen, *Arch. f. Physiol.*, 1884, 521.

[8] J. von Kries, in Helmholtz' *Handbuch der physiologische Optik*, ii, 1911, 345.